

Accepted by Ap. J. in April 2004.

Properties and Interpretations of Giant Micropulses and Giant Pulses from Pulsars

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ABSTRACT

Giant pulses and giant micropulses from pulsars are distinguished from normal pulsed emission by their large fluxes, rarity, approximately power-law distribution of fluxes and, typically, occurrence in restricted phase windows. Here existing observations of flux distributions are manipulated into a common format and interpreted in terms of theories for wave growth in inhomogeneous media, with the aim of constraining the emission mechanism and source physics for giant pulses and micropulses. Giant micropulses near 2 GHz (PSRs B8033-45 and B1706-44) and 0.4 GHz (PSR B0950+08) have indices $\alpha = 6.5 \pm 0.7$ for the probability distribution $P(E)$ of the electric field E , with $P(E) \propto E^{-\alpha}$. Giant pulses (PSRs B0531+24, B1937+214, and B1821-24) have α ranging from 4.6 ± 0.2 to 9 ± 2 , possibly increasing with frequency. These are similar enough to regard giant micropulses and pulses as a single phenomenon with a common physical explanation. The power-law functional form and values of α observed are consistent with predictions for nonlinear wave collapse, but inconsistent with known self-organized critical systems, nonlinear decay processes, and elementary burst theory. While relativistic beaming may be important, its statistics are yet to be predicted theoretically and collapse is currently the favored interpretation. Other possibilities remain, including stochastic growth theory (consistent with normal pulse emission) and, less plausibly, refractive lensing. Unresolved issues remain for all four interpretations and suggestions for further work are given. The differences between normal and giant pulse emission suggest they have distinct source regions and emission processes.

Subject headings: pulsars: general — pulsars: individual (Vela) — methods: statistical — plasmas — radiation mechanisms: non-thermal — stars: neutron

1. Introduction

Giant pulses from the Crab pulsar (B0531+24), defined as pulses whose pulse-integrated fluxes F_{tot} exceed ten times the average pulse-integrated flux $F_{av,tot}$, were intrinsic to discovery of the Crab pulsar (Staelin & Reifenstein 1968; Heiles et al. 1970) and have been studied extensively since (Lundgren et al. 1995; Sallmen et al. 1999; Hankins et al. 2003). They are remarkable for several reasons other than their very large fluxes, which are sometimes hundreds to thousands of times larger than $F_{av,tot}$. First, only the Crab pulsar and the millisecond pulsars B1937+214 and B1821-24 (Cognard et al. 1996; Romani and Johnston 2001) are known to produce giant pulses. Second, giant pulses are produced sometimes in the same phase windows as the normal pulses, for the Crab pulsar (Staelin & Reifenstein 1968; Heiles et al. 1970) and PSR B1821-24 (Romani and Johnston 2001), but also in narrow phase windows trailing the main pulse and interpulse for PSR B1937+214 (Cognard et al. 1996). Third, their distribution of fluxes appears to be a power-law and is usually considered to be clearly distinguishable from that for normal pulses (Lundgren et al. 1995; Cognard et al. 1996). Indeed, the distribution of pulse-integrated fluxes for normal pulses often appears approximately Gaussian when binned in the logarithm of the flux [e.g., (Johnston et al. 2001)], and so is approximately lognormal, and phase-resolved flux distributions for normal pulses are often interpretable in terms of a lognormal distribution or the vector convolution of a lognormal with either a Gaussian or lognormal distribution (Cairns et al. 2001, 2003a,b,c). The importance of the (electric) field statistics is that they are determined by the source physics, emission mechanism, and propagation effects (Cairns et al. 2001, 2003a), as well as relativistic beaming effects: accordingly, different flux distributions imply different emission mechanisms and/or source regions for giant pulses and the normal pulses, as surmised on intuitive grounds previously (Romani and Johnston 2001).

Giant micropulses have been discovered very recently for the Vela pulsar (B8033-45) and pulsars B1706-44 and B0950+08 (Johnston et al. 2001; Kramer et al. 2002; Johnston & Romani 2002; Cairns et al. 2003c). These are short-duration intense events that have phase-resolved fluxes much greater than ten times the average flux for that phase, but have pulse-integrated fluxes less than 10 times the average and so are not giant pulses. Importantly, giant micropulses also appear to have approximately power-law distributions of flux, are rare, do not occur for every pulsar (Johnston & Romani 2002), and occur in narrow phase windows either leading [Vela (Johnston et al. 2001) and B0950+08 (Cairns et al. 2003c)] or trailing [PSR B1706-44 (Johnston & Romani 2002)] the average pulse peak. These features all point to strong similarities between giant micropulses and giant pulses. Indeed, it is sometimes suggested that giant pulses and micropulses are generated near the light cylinder, in a similar fashion to the outer-gap model for X-ray and/or gamma ray pulses (Romani & Yadigaroglu 1995; Romani and Johnston 2001; Johnston & Romani 2002). This paper

compares the observed field statistics with theoretical predictions to constrain the emission mechanism responsible for giant pulses and giant micropulses.

Growth of plasma waves and radiation in inhomogeneous plasmas, and its propagation between source and observer, naturally results in bursty, time-variable radiation. Multiple theories exist for the associated field statistics, differing due to varying degrees of self-consistent interaction between the waves, driving particles, and background plasma, the detailed emission mechanisms producing the waves, the importance of scattering, and the number of wave populations contributing. The giant and “normal” components of pulsar radio emissions have been discussed in terms of several collective (or coherent) emission mechanisms, including: (i) linear plasma instabilities such as curvature emission and beam instabilities [e.g., Melrose (1996); Gedalin et al. (2002)], (ii) linear mode conversion (Melrose & Gedalin 1999; Cairns et al. 2001), and (iii) nonlinear modulational instabilities and collapse of wavepackets (Asseo, Sol, & Pelletier 1990, Asseo 1996, Weatherall 1997, 1998, Hankins et al. 2003). Theoretical frameworks considered include self-organized criticality [SOC] (Bak et al. 1987; Bak 1996; Young & Kenny 1996), stochastic growth theory [SGT] (Robinson 1992; Cairns & Robinson 1999; Robinson & Cairns 2001; Cairns et al. 2001, 2003a,b), and nonlinear structures (Pelletier, Sol, & Asseo 1988, Asseo 1996, Weatherall 1997, 1998). Other possibilities include refractive lensing events due to propagation through density inhomogeneities (M.A. Walker, personal communication, 2003) and time-variable relativistic beaming effects. As summarized below, these emission mechanisms and theoretical frameworks predict different field statistics, so that comparisons between theory and observation permit the emission mechanism and source physics to be constrained. Recent analyses do this for normal pulses of the Vela pulsar and pulsars B1641-45 and B0950+08 (Cairns et al. 2001, 2003a,b,c).

The goals of this paper are to: (1) show that the distributions of electric field strengths for known sources of giant pulses and giant micropulses are all approximately power-law at high fluxes and have sufficiently similar power-law indices for them to be regarded as one population, (2) constrain which models for emission processes and source physics for giant pulses/micropulses remain viable, by comparing observations with theoretical predictions, (3) show that wave collapse is the most favored interpretation for giant pulses and micropulses, in the absence of detailed calculations for relativistic beaming, while some other interpretations appear viable but less plausible and others are inconsistent with available data, and (4) point out limitations in current theories for wave collapse. These goals are addressed by summarizing theory for field statistics (Section 2), analyzing and discussing the field statistics of giant micropulses (Section 3) and giant pulses (Section 4), and comparing the observations with theoretical predictions (Section 5). The results are summarized and brief conclusions given in Section 6.

2. Summary of Relevant Theories for Field Statistics

The pulsar plasma is expected to be significantly time-variable. Accordingly, relativistic beaming effects might lead to significant variations in the observed fields due to changes in the Lorentz factor Γ and the direction of primary emission relative to a stationary observer, thereby potentially modifying the intrinsic field statistics of a specific mechanism in the source rest frame. Detailed reasons include the following. First, the observed flux varies as Γ^{-3} (Weatherall 1997), where Γ is the Lorentz factor. Second, the angular distribution of radiation becomes increasingly directed in the forward direction (along \mathbf{v}) as Γ increases. Third, temporal changes in the emission direction relative to a stationary observer may occur: for instance, Alfvén waves or other disturbances might cause the bundle of magnetic field lines carrying an active emission source to move the relativistic beaming pattern into an observer’s viewing window at some times and not at other times. Unfortunately predictions do not yet exist for the distributions $P(F)$ resulting from variations in Γ and the relative viewing angle, which will depend at least on the statistics of Γ , the source location, and the variability of the magnetic field and flow velocity of the source plasma.

A qualitative argument suggests that relativistic beaming effects for a single emission mechanism and single source plasma can not determine the field statistics of all components of pulsar emission: if they did, then the field statistics of all emission components would have the same functional form. This is contrary to normal pulsar emission having lognormal statistics (Cairns et al. 2001, 2003a,b,c) and giant pulses and micropulses having power-law statistics, as described below. Instead, if all components involve relativistic beaming then it seems clear that these different statistics must require different source conditions (e.g., distributions of Γ and/or relative emission angle) and/or different emission mechanisms. It is undoubtedly true that relativistic beaming effects are important for pulsar emissions. Nevertheless, in the current absence of theoretical calculations that show how relativistic beaming can modify intrinsic field statistics or produce qualitatively different field statistics for different source conditions or mechanisms, attention is focused below on mechanisms that do not involve relativistic beaming effects.

Several theories exist for wave growth in inhomogeneous media, each predicting different field statistics which can be used to constrain the source physics and emission mechanism, including whether nonlinear processes are active. These theories, their justifications, and predictions are detailed elsewhere (Bak et al., 1987; Robinson & Newman 1990; Robinson 1992, 1995, 1997; Robinson et al. 1993; Bak 1996; Cairns & Robinson 1999; Robinson & Cairns 2001; Cairns et al., 2001, 2003a) and only a brief summary is given here. Define the probability distribution $P(E)$ of the (electric) field E and the related distributions $P(E^2) \propto P(F)$ of the field energy E^2 and flux F , with $F \propto E^2$. These distributions are normalized

according to $\int P(X)dX = 1$ where $X = E$, E^2 , or F .

SOC involves fully self-consistent interactions near marginal stability between the waves, driving particles, and the background plasma (Bak et al. 1987; Bak 1996): the system is driven away from stability but then relaxes towards marginal stability, with no preferred scales over large ranges of distance or time. SOC predicts a power-law distribution of energy releases over many decades with index $\beta \approx 1$, with a range $\approx 0.5 - 2$ in known systems (Bak 1996). Then, assuming that the energy releases are adequately represented by the individual flux samples measured over some integration time (implying that event duration is unimportant, an assumption that remains to be checked observationally), so that

$$P(F) \propto F^{-\beta} , \quad (1)$$

SOC predicts a power-law with

$$P(E) \propto E^{-\alpha} . \quad (2)$$

Since $2EP(E^2) = P(E)$ via the normalization conditions, (1) and (2) imply $\alpha = 2\beta - 1$, whence $\alpha \approx 1$ with a range $\approx 0 - 3$ in known SOC systems. SOC has been suggested for giant pulses (Young & Kenny 1996) and also for X-ray variability of active galactic nuclei (Bak et al. 1988).

The nonlinear self-focusing process of modulational instability typically leads to wave collapse, in which a wavepacket collapses to smaller spatial scales while intensifying, as reviewed elsewhere (Robinson 1997; Weatherall 1997). Non-relativistic electron-proton simulations of Langmuir waves show that modulational instability leads to wave collapse in two or three dimensions with power-law statistics at high E described by (2) (Robinson 1997). These simulations and associated scaling theory show that the index α depends strongly on the dimensionality D and shape of the collapsing wavepackets (isotropic versus prolate versus oblate shapes relative to the magnetic field direction and whether the field energy $W \equiv E^2$ is above or below the mean energy $\langle W \rangle$), as summarized in Table 1 (Robinson & Newman 1990; Robinson 1996). Simulations that include electromagnetic effects for strongly magnetized, relativistic, electron-positron plasmas appropriate to pulsars also show wave collapse proceeding (Weatherall 1997, 1998). However, although these collapse events are qualitatively very similar to those for the electron-proton simulations, the statistics of the collapsing fields have not been published. It might be objected that modulational instability can lead to stable solitons and not collapse. However, this appears to be true only under restrictive conditions: for instance, only in one dimension (rather than two or three) does modulational instability leads to stable solitons rather than collapse for the electron-proton simulations described above (Robinson 1997). Similarly, for the electron-positron plasmas above, purely electrostatic calculations suggest that solitons are modulationally stable (Pelletier et al. 1988;

Table 1: Power-law indices α for the $P(E) \propto E^{-\alpha}$ distribution obtained from numerical simulations and scaling theory for wave collapse (Robinson and Newman 1990, Robinson 1997). The dimension D is either 2 or 3.

Range of E	Isotropic	Prolate	Oblate
$E < \langle W \rangle^{1/2}$	$-(2D - 1)$	$-(2D - 3)$	-1
$E > \langle W \rangle^{1/2}$	$D + 2$	$D + 3$	$2D + 1$

Asseo et al. 1990) but inclusion of electromagnetic effects leads to wave collapse in simulations (Weatherall 1997, 1998). Accordingly, it is presumed that modulational instability leads to wave collapse and power-law statistics with indices similar to those given in Table 1 for electron-proton calculations. Possible differences in the indices for pulsar magnetospheres are discussed in Section 5.2.

Table 1 shows that collapse should produce negative α (corresponding to $P(E)$ increasing with E) for field energies less than the mean value $\langle W \rangle$, whereas α should be positive above the peak in $P(E)$ with integer values in the range 4 – 7 that depend significantly on D and the wavepacket shape. Importantly, these indices for high E are significantly larger than those for known SOC systems, so that systems involving collapse should usually be distinguishable from SOC systems. The origin of these collapsing wavepackets is usually assumed to be a plasma instability, thereby potentially involving SGT, as discussed next.

SGT (Robinson 1992; Robinson et al. 1993; Robinson 1995; Cairns & Robinson 1999; Robinson & Cairns 2001) treats systems in which an unstable particle distribution and associated waves driven by an instability couple self-consistently in an independent, spatially-inhomogeneous medium, causing the wave-particle system to fluctuate stochastically about marginal stability. Pure SGT then predicts lognormal statistics for E :

$$P(\log E) = (\sqrt{2\pi} \sigma)^{-1} e^{-(\log E - \mu)^2 / 2\sigma^2}, \quad (3)$$

where $\mu = \langle \log E \rangle$ and σ are the average and standard deviation of $\log E$, respectively, and $\log \equiv \log_{10}$ for future convenience. SGT is widely applicable in solar system plasmas (Robinson et al. 1993; Cairns & Robinson 1999; Cairns & Grubits 2001; Cairns & Menietti 2001) and also describes very well the phase-resolved statistics of normal pulses from several pulsars (Cairns et al. 2001, 2003a,b,c).

SGT can coexist with a nonlinear process active at high $E \geq E_c$. In this case, the $P(\log E)$ distribution is modified in two characteristic ways from the lognormal predicted

for pure SGT : (i) if a decay process removes energy from the primary (parent) waves, then the $P(\log E)$ distribution is reduced near and above E_c with known form (Robinson et al. 1993; Robinson 1995; Cairns & Grubits 2001; Cairns & Menietti 2001); (ii) if a nonlinear self-focusing process like wave collapse or modulational instability (Robinson 1997) is active, increasing the number of intense wavepackets, then the field distribution is enhanced at high $E \geq E_c$ into a power-law tail with index given in Table 1.

Thermal waves driven by an instability and subject to limited stochastic growth effects (but which have not evolved into a pure SGT state) have approximately power-law statistics at fields much greater than the average thermal level E_T (Robinson 1995; Cairns et al. 2000): the index α in (2) is positive, depends on the difference between the average growth and damping rates divided by a stochastic parameter, and can take a wide range of possible values. Importantly, though, the majority of the fields will be within a few decades of E_T .

Gaussian intensity statistics result from superposition of multiple random signals, as expected for measurement noise, sky background, and multiple unresolved subsources:

$$P(I) = (\sqrt{2\pi} \sigma_I)^{-1} e^{-(I-I_0)^2/2\sigma_I^2} . \quad (4)$$

In addition, closely Gaussian intensity statistics can result from scattering of radiation by density inhomogeneities between the source and observer under some circumstances (Ratcliffe 1956; Salpeter 1967; Rickett 1977). Refractive focusing can also lead to “lensing” events associated with caustics and other singularities (M.A. Walker, personal communication, 2003). In particular, Walker pointed out that the magnification depends on the geometric properties of caustics: he used established results from gravitational lensing theory [Equation (11.64a) of Schneider et al. (1992)] to show that the distribution of flux magnification factors $\mu = F/F_0$ for the lowest order critical curve (a fold) is power-law at large μ , with

$$P(\mu) \propto \mu^{-3} , \quad (5)$$

where F_0 is the original flux. Convolving this distribution with an initial distribution of fluxes leads to the result (1) with $\alpha = 3$ at large F . Independently, the Referee pointed out that a direct analysis of lensing effects in scattering theory [Equation (28a) of Salpeter (1967)] yields the form (1) with $\alpha = 3$.

Predictions exist for the statistics of “elementary burst” systems (Robinson et al. 1996) and uniform secular growth (Cairns & Robinson 1999). However, these are considered very unlikely to be relevant and are not detailed here.

3. Statistics for Giant Micropulses

3.1. PSR B1706-44

Johnston & Romani (2002) observed giant micropulses from PSR B1706-44 at 1.5 GHz. They claimed that giant micropulses are separable from the normal pulse emission since at large F the (non-standard) cumulative probability distribution $\text{CDF}(F)$, calculated using logarithmic binning in F according to their Figure 4, changes to a power-law function with

$$\text{CDF}(F) = \int_F^\infty d(\log F) P(\log F) \propto F^{-\beta} \quad (6)$$

and $\beta \approx 2.7 \pm 0.3$, the error being estimated by eye from their figure 4. [The usual cumulative probability distribution equals $1 - \text{CDF}(F)$ and $\log = \log_{10}$ here and below.] That figure shows the transition to an approximately power-law distribution occurring near $F = 10^{2.5}$ mJy, where 1 jansky (Jy) equals $10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$.

Consider now the field and intensity proxies E' and I' , defined in terms of F by

$$E' = (F/1\text{mJy})^{1/2}, \quad (7)$$

$$I' = F/1\text{mJy}. \quad (8)$$

These proxies are proportional to the actual field E and intensity I incident on the antenna, which are used in (4) and (3), respectively, and are used henceforth without prime symbols.

Now, since $F \propto E^2$ and $P(\log E) = EP(E)$, it is easy to show that (6) leads to the form (2) with $\alpha = 2\beta + 1 = 6.4 \pm 0.6$ for B1706-44's giant micropulses (Table 2). It is important to ascertain whether the flux observations are binned in linear rather than logarithmic bins: since linear binning would correspond to (6) in the form $\int dX P(X)$ with $X = F$ rather than $\log F$, and since $P(\log F) = FP(F)$, mistaking linear for logarithmic binning (or vice versa) leads to a difference of 2 in the index α .

Table 2 also lists the range of $\log F$ for which power-law statistics are observed (0.5 for B1706-44), which might appear large enough for reasonable confidence to be attached to the inferred value of α . However, as discussed in Section 5, apparently power-law statistics can arise due to vector superposition of lognormal and Gaussian distributions (Cairns et al. 2002, 2003b).

3.2. The Vela pulsar

Giant micropulses from the Vela pulsar at 2.3 GHz also have apparently power-law statistics at large F that obey the form (6), this time with $\beta \approx 2.85 \pm 0.3$ (Kramer et

Table 2: Power-law indices α observed for the $P(E) \propto E^{-\alpha}$ distribution of giant pulses (GP) and giant micropulses (GM). Also given are the observing frequency and the observed range of the power-law statistics, measured in \log_{10} of the flux F in mJy (units of $10^{-29} \text{ Wm}^{-2}\text{Hz}^{-1}$).

Pulsar	B1706-44	Vela	B0950+08	Crab	B1937+214	B1821-24
Type	GM	GM	GM	GP	GP	GP
Frequency (GHz)	1.5	2.3	0.4	0.8	0.4	1.5
Range of $\log F$	0.5	0.5	0.8	1.0	2.0	0.1
α	6.4 ± 0.6	6.7 ± 0.6	6.2 ± 0.5	5.6 ± 0.6	4.6 ± 0.2	9 ± 2

al. 2002), where the error is again estimated by eye. Converting into the form (2), as for B1706-44, leads to $\alpha = 6.7 \pm 0.6$.

3.3. Pulsar B0950+08

Giant micropulses from B0950+08 at 0.43 GHz have apparently power-law statistics at large F that obey the form (2) with index $\alpha = 6.2 \pm 0.5$ (Cairns et al. 2003c). These giant micropulses are observed over a relatively large range of pulsar phase compared with those for Vela and B1706-44. Several other classes of emissions were identified with approximately power-law statistics. However, their indices were substantially less, with values in the range 1 – 4.

Summarizing, the field distributions observed near 2 GHz and 0.4 GHz for giant micropulses from three pulsars (Vela, B1706-44, and B0950+08) can be interpreted in terms of power-laws with high indices $\approx 6.5 \pm 0.7$. These limited data provide no evidence for α varying with observing frequency.

4. Field Statistics For Giant Pulses

Giant pulses from the Crab pulsar also have apparently power-law statistics at large F : binning linearly in F , the distribution is well described by (Lundgren et al. 1995)

$$P(F) \propto F^{-\gamma} \quad (9)$$

with $\gamma = 3.3 \pm 0.3$ at 800 MHz. Here 3.3 is the most common value observed for the exponent and the “error” is the difference between the largest and smallest values observed (Lundgren et al. 1995). Then, since $P(E) = 2EP(E^2)$, (9) can be placed in the form (2) with $\alpha = 2\gamma - 1 = 5.6 \pm 0.6$.

Giant pulses from the millisecond pulsar B1937+214 at 430 MHz also appear to be power-law distributed (Cognard et al. 1996). Inspection of their Figure 3 suggests that the cumulative distribution is binned logarithmically, not linearly, whence (6) applies with $\beta = 1.8 \pm 0.1$ at 430 MHz. Accordingly (2) holds with $\alpha = 4.6 \pm 0.2$. [Note that linear binning would imply $\alpha = 2.6 \pm 0.2$, a clear difference.]

Taken together the results for the Crab and B1937+214 are consistent with giant pulses having power-law statistics with high indices $\approx 4.4\text{--}6.2$, and are only marginally inconsistent with them having a common index. Both possibilities, that these giant pulses have a common index and that they have different indices, need further consideration. In this connection, giant pulses detected from the millisecond pulsar B1821-24 (Romani and Johnston 2001), despite the very limited quantity of data, may be significant. The data provide very weak evidence that the cumulative probability distribution (6) is power-law with $\beta \approx 3 - 5$ and so $\alpha = 7 - 11$. Although little confidence can be attached to these estimates prior to more extended observations, they hint that the range of α for giant pulses overlaps the values for giant micropulses and that the large inferred range for α , from ≈ 4.5 to at least 6.5 is real. Since the three sets of observations for giant pulses are for widely different frequencies (800 versus 430 and 1517 MHz) it is possible that the apparent spread in α is real and corresponds to α increasing with observing frequency, reaching the range observed for giant micropulses only above 1 GHz. On the other hand, since the background of normal pulses is larger at lower frequencies, the apparent trend in α for giant pulses may be due to convolution of giant and “normal” emission.

The foregoing observations and associated analyses imply, *prima facie*, that both giant pulses and giant micropulses can be interpreted in terms of power-law statistics with high values of α in the ranges 4.4–11 and 6.5 ± 0.7 , respectively. While the data suggest that α may increase with observing frequency for giant pulses but not giant micropulses (Table 2), these indices are similar enough to suggest a common interpretation for both giant phenomena.

5. Constraints on the Emission Mechanisms and Source Physics

5.1. Basic issues and SOC

Giant pulses and micropulses are frequently restricted to narrow phase windows compared with the normal pulse emission. They also occur as higher flux events than normal pulses and have observably different field statistics. These characteristics are strong evidence that giant pulses and micropulses are generated in a different source region and/or by a different emission process than the normal pulsar emissions, which can almost certainly be interpreted in terms of SGT, based on analyses for three pulsars (Cairns et al. 2001, 2002, 2003a,b). One interpretation is that giant phenomena are generated in the neutron star’s outer magnetosphere, associated with an outer gap plasma, while the normal pulses are generated in the inner magnetosphere near the inner gap (Romani & Yadigaroglu 1995; Romani and Johnston 2001).

In general, the observed field statistics are determined by the intrinsic field statistics produced by relevant generation mechanisms, relativistic beaming effects, possible spatial variations across the source, and propagation effects. Relativistic beaming effects may be very important for the $P(E)$ distribution, due to intrinsic variations in Lorentz factor and emission direction inside the source (Section 2). However, until the field statistics are calculated for relativistic beaming, the importance of this effect cannot be evaluated quantitatively. Beaming effects are therefore neglected for the rest of this section.

Consider next propagation effects and associated refractive lensing by density irregularities. Ordinary propagation effects are discounted, since they likely produce approximately Gaussian intensity statistics (Ratcliffe 1956; Salpeter 1967; Rickett 1977) and appear relatively unimportant for normal pulses (Cairns et al. 2001, 2003a,b,c). Following Salpeter (1967) and Walker (personal communication, 2003) as described in Section 2, refractive lensing events should produce $P(F) \propto F^{-3}$, whence (1) and (2) imply $P(E) \propto E^{-5}$. Comparing this prediction with Table 2, lensing appears viable for giant pulses from the Crab pulsar, but marginally inconsistent with giant pulses from B1937+214 and B1821-24 (although α is very poorly known for the latter) and significantly inconsistent for the three known sources of giant micropulses. Moreover, this mechanism predicts that α should be independent of frequency, plausibly inconsistent with Table 2’s data for giant pulses. It may be relevant, however, that under some conditions the superposition of lensing events onto the distribution of normal pulses, and the reduced range of F observed in the present datasets, may increase α , perhaps as found for giant micropulses. In summary, at present the available data appear inconsistent with lensing and scattering effects being important for both giant pulses and giant micropulses, but are not yet definitive.

With relativistic beaming and refractive effects discounted at this time, the simplest interpretation is adopted: the observed field statistics are intrinsic (perhaps involving more than one mechanism) and not significantly influenced by spatial variations or relativistic beaming effects in the source. Progress can then be made in restricting the emission mechanism and source physics responsible for giant micropulses and pulses. The approximately power-law functional form of the observed field distribution is inconsistent with thermal waves, uniform secular growth, and elementary burst systems (modified Rayleigh, uniform, and exponential statistics, respectively) and with waves subject to nonlinear decay processes. Driven thermal waves, while they develop power-law statistics at high E (Robinson 1995; Cairns et al. 2000), are a most unlikely explanation since the observed brightness temperatures are many orders of magnitude larger than plausible thermal temperatures.

SOC might appear attractive since it predicts power-law statistics. However, the power-law indices estimated directly are $\approx 4-7$, differing greatly from 1 and lying outside the range $0.5-3$ typical of phenomena interpreted in terms of SOC (Bak 1996). Accordingly, it is doubtful that SOC applies to giant pulses and micropulses, contrary to an earlier qualitative suggestion (Young & Kenny 1996). Reversing this conclusion requires that (1) the index for the distribution of giant micropulses/pulses is much lower than that estimated directly, perhaps due to the convolution effects mentioned in subsection 5.3 below, and/or (2) a theoretical model based on SOC can be developed with such large power-law indices.

5.2. Wave collapse

The nonlinear self-focusing process of wave collapse leads directly to power-law statistics at high E (Robinson & Newman 1990; Robinson 1996) and so is immediately attractive for giant pulses and micropulses. Moreover, the indices $4.4-7.3$ (including the error bounds) determined directly for the four pulsars with reasonably well-determined field statistics (Table 2 excluding PSR B1821-24) overlap with the range $4-7$ predicted for wave collapse in non-relativistic, electrostatic, electron-proton simulations (Robinson & Newman 1990; Robinson 1996). In particular, substituting $D = 2$ or 3 into the results in Table 1, isotropic collapse theory predicts $\alpha = 4$ and 5 , with the corresponding predictions for prolate and oblate wavepacket shapes (appropriate to magnetized conditions) being $\alpha = 5, 6$ and $5, 7$, respectively. Accordingly, interpretations in terms of modulational instability and wave collapse appear viable for giant micropulses and pulses: earlier work for normal pulses (Weatherall 1997, 1998) may thus be relevant to giant phenomena instead. Very recent analyses of short timescale structures observed in giant pulses from the Crab pulsar (Hankins et al. 2003) provide qualitative support for the conclusion reached here.

Three points of concern should be raised, however. First, although waves undergoing collapse in relativistic, electron-positron, strongly magnetized plasmas appropriate to pulsar magnetospheres are expected to have power-law statistics, based on the strong qualitative similarities with collapse in electron-proton plasmas (Weatherall 1997, 1998), the power-law indices are not yet known. Specifically, the very different wave dispersion, nonlinearities, magnetization effects, and electromagnetic character (Melrose & Gedalin 1999; Gedalin et al. 2002) could well alter the collapse dynamics and so the predicted indices from those known (Robinson 1997) for non-relativistic electron-proton simulations. More work is thus required to make wave collapse into a fully quantitative theory for giant pulses and micropulses.

Second, weak evidence exists (Section 4) that α increases with observing frequency for giant pulses but not giant micropulses, corresponding either to an increase in D and/or a change in wavepacket shape. While this may be possible, the standard model of pulsar magnetospheres is that the plasma density and magnetic field strength decrease monotonically with distance from the pulsar (once well above the inner gap region), whence it is more plausible that D should increase, and magnetization effects decrease (corresponding to more isotropic wavepackets), with increasing height and so decreasing frequency. This qualitative argument predicts α should decrease with increasing frequency, opposite to the apparent trend in α for giant pulses. Given the possible importance of convolution effects, discussed more in subsection 5.3, the trend in α may be affected by sensitivity issues and variations in the observed flux relative to the receiver noise with frequency. This should be addressed in future multi-frequency observations.

Third, suppose two or more processes combine to produce the observed field statistics, for instance because collapsing wavepackets generate radiation at the electron plasma frequency and/or its harmonics via a nonlinear process or an antenna mechanism (Freund and Papadopoulos 1980; Hafizi & Goldman 1981; Akimoto et al. 1988). [Note that linear mode conversion, or direct escape of the collapsing wavepacket from the source region before “burnout”, should not alter the field statistics from those predicted by collapse theory.] Then, combining a nonlinear process whose rate is proportional to, say, W^2 (or E^4) with the wavepacket statistics given by Table 1, the overall statistics should still be power-law but with a larger index α' (ideally with $\alpha' = \alpha + 4$) than predicted in Table 1. Further theoretical work is required to assess this possibility, for collapse, SOC, and potentially other theories.

5.3. Convolution effects and SGT

It is emphasized now that closely power-law statistics for 1 – 2 decades in E (2 – 4 decades in F) can result (Cairns et al. 2002, 2003b) from vector superposition of a Gaussian

(intensity) or lognormal distribution with a lognormal distribution centered at lower E but extending to higher E (due to larger σ in equation 3). Exactly this effect appears relevant in the “transition regions” of three pulsars, explaining the statistics of normal pulses at pulsar phases where the normal pulsar emission is just becoming observable above the background (Cairns et al. 2003a,b,c). Table 2 shows that the giant pulses and micropulses are observed over at most 2 decades in F . Accordingly, two crucial observational questions remain to be answered: (1) are the apparently power-law statistics observed for these giant phenomena intrinsic or are they due to vector superposition of two or more distributions (with the combination of a lognormal with either a Gaussian intensity distribution or another lognormal known to produce the effect)? (2) If intrinsic, are the power-law indices significantly affected by superposition of the giant micropulses with the distribution of normal pulses and/or receiver noise?

These issues therefore affect whether SGT is a viable theory for giant pulses and micropulses. A single wave population obeying pure SGT is predicted to yield lognormal statistics; this simple interpretation is then inconsistent with the data. However, there are at least two ways in which the apparently power-law statistics for giant pulses and micropulses can be reconciled with SGT. First, as pointed out just above, vector convolution of a lognormal with either a Gaussian intensity distribution (e.g., sky background and receiver noise) or a second lognormal can result in field statistics that appear closely power-law for a broad range of high fluxes/fields (Cairns et al. 2002, 2003b,c). Second, SGT can coexist at moderate E with wave collapse at high E (Robinson 1995; Cairns et al. 2003a), resulting in a power-law distribution at high enough E (above the peak in the SGT distribution), as discussed in Section 2.

Longer duration observations which determine the field statistics over larger ranges of F are required to answer these questions definitively. Reasons are that the extent of the range in F over which the statistics are approximately power-law will become apparent, as will changes in the statistics at large F . The second reason relates to the fact that if the apparently power-law statistics are due to vectorial superposition of two non-power-law distributions or one power-law distribution with a non-power-law distribution, then at high enough F the functional form of the combined distribution will evolve to that of the component distribution which dominates at large F (Cairns et al. 2002).

6. Summary and Conclusions

(1) The different statistical properties of giant pulses and micropulses from the normal pulsar emission, and the restricted phase windows in which they are typically observed

(except for the Crab pulsar and B0950+08), imply that the giant and normal emissions are most likely produced in distinct source regions via different emission mechanisms.

(2) The power-law indices estimated directly from the field distributions for the three known sources of giant micropulses at 0.4, 1.5 and 2.3 GHz are almost identical at 6.5 ± 0.7 , so that they may be regarded as one population with similar source physics.

(3) The power-law indices estimated directly from observations of known sources of giant pulses are 4.6 ± 0.2 , 5.6 ± 0.6 , and $7 - 11$ at 430, 800, and 1.5 GHz, respectively. The indices may increase with observing frequency, perhaps reaching the values for giant micropulses above 1 GHz. If real this trend suggests a difference from giant micropulses, but the trend may be due to the relative background varying with frequency.

(4) The power-law indices of giant pulses and giant micropulses appear to be sufficiently similar for them to have a common theoretical interpretation.

(5) It is not yet established conclusively that the apparently power-law field statistics of giant micropulses and pulses are intrinsic rather than the result of vectorially convolving two non-power-law distributions. Such non-intrinsic power-law statistics are found for normal pulses in the transition regions where the normal pulsar emissions are emerging above the background (Cairns et al. 2003b,c). Extended observations of giant micropulses and pulses are required, with fitting of at least two wave components, to determine whether the observed power laws are intrinsic at high F and, if so, what the true power-law indices are. This requires longer-duration observations so as to obtain better statistics and observe events over a larger range of fluxes.

(6) Relativistic beaming effects, which produce variations in observed flux due to changes in Lorentz factor and the direction of maximum emission relative to the observer (e.g., due to magnetic turbulence or changes in the plasma flow velocity), might be relevant. Theoretical models for the ensuing flux statistics are required, with high priority since pulsar plasmas are certainly relativistic and pulsar emissions are clearly beamed.

(7) Emission mechanisms involving thermal waves, driven thermal waves, uniform secular growth, elementary burst systems, and nonlinear decay mechanisms are inconsistent with the functional form of the observed distribution. The first two are also implausible on energy grounds. Lensing events due to refraction by density irregularities are interesting since they produce power-law field statistics (M.A. Walker, personal communication, 2003) with $\alpha = 5$. This value is consistent with giant pulses from only one pulsar (the Crab), but not the giant micropulses or the apparent variation of α with observing frequency. Observational limitations mean that this mechanism cannot yet be ruled out.

(8) The power-law indices $\approx 4.4 - 7$ estimated directly from the observed distributions differ greatly from the value ≈ 1 for simple SOC theory and lie outside the range $\approx 0.5 - 3$ of known SOC systems. SOC is therefore implausible despite the statistics being power-law. Reversing this conclusion requires, first, further observations confirming that the giant phenomena have intrinsic power-law statistics whose indices were significantly overestimated due to convolution effects with the normal pulses and measurement noise and/or, second, construction of theoretical SOC models with suitably large values of α .

(9) Nonlinear modulational instabilities and wave collapse processes typically have power-law field statistics, qualitatively consistent with the available data. Moreover, the observed indices $\alpha \approx 4.4 - 7$ lie within the range $4 - 7$ predicted by current theories for wave collapse (Robinson & Newman 1990; Robinson 1996). This is currently the most plausible mechanism for giant pulses and micropulses, complementing another argument based on timescales (Hankins et al. 2003).

(10) Further research on applying collapse theory and modulational instabilities to giant pulses and micropulses is required to resolve open issues relating to (i) whether the field statistics for collapse in the relativistic, electron-positron, highly magnetized plasmas in pulsar magnetospheres differ from those known for non-relativistic electron-proton plasmas, (ii) explaining the apparent trend in α with observing frequency for giant pulses being opposite to that predicted qualitatively based on magnetization effects and current collapse theory, and (iii) considering in detail how collapse produces the observed radiation and how any ancillary radiation mechanism modifies the predicted field statistics.

(11) Finally, SGT cannot yet be ruled out as important in understanding giant pulses and micropulses since (i) the observed power-law statistics can be interpreted in terms of vector convolution of one or more of the lognormal distributions predicted for SGT, as already observed for normal pulses (Cairns et al. 2002, 2003b,c), and (ii) wave collapse and SGT can coexist. The differences between normal and giant pulsar emission favor, but do not require, a different theoretical interpretation for the two phenomena, thereby favoring wave collapse over SGT for giant pulses and micropulses.

In conclusion, progress has been made in determining the intrinsic field statistics of giant micropulses and giant pulses and identifying therefrom the source physics and emission mechanisms. Both phenomena appear to have very similar field statistics and to admit a common theoretical interpretation, although whether the observed power-law features are intrinsic or due to convolution effects remains to be determined. The nonlinear process of wave collapse produces power-law statistics with indices that can be in the observed range and, despite some theoretical difficulties, appears the most plausible theoretical interpretation. SGT remains viable although less favored, while SOC, refractive lensing, and certain

other mechanisms appear not viable. Relativistic beaming effects due to changes in Lorentz factor and emission direction still need to be investigated and are plausibly very important. Longer duration, more sensitive observations of giant phenomena over a larger range of fluxes, together with associated fitting of multiple vectorially-convolved wave distributions should resolve these observational issues. Outstanding theoretical issues may be resolved by extending current simulations and theories for relativistic beaming and wave collapse, together with any other radiation mechanisms required, to conditions appropriate for pulsar magnetospheres.

I thank the Referee for emphasizing the possible importance of relativistic beaming effects, M. A. Walker for personal communications involving refractive lensing events, and S. Johnston, M. A. Walker, and P. A. Robinson (all at U. Sydney) for helpful discussions and comments on this paper. The Australian Research Council funded this research.

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